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DESIGN AND DEVELOPMENT OF RELIABLE GUN-FIRED STRUCTURES

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14. ABSTRACT

Precision munitions must be strong enough to exit the gun tube without damage to the gun, safe enough for the soldiers near the gun, accurate, and reliable. Precision munitions carry computers, circuit boards, guidance and control systems, heat sensors, infrared sensors, safety and arming devices, and payloads. Gun-fired systems are expected to survive high g-forces in the gun tube and then guide the weapon to target. Precision munitions routinely meet safety and accuracy requirements. The reliability requirements have been more difficult to meet. This paper describes methods to improve structural reliability. The process includes uncertainties at all levels of the development process. The process should lead to more reliable weapon systems and shorter time to field a system to the soldier.

15. SUBJECT TERMS

Excalibur, Design, Dynamic, Static, Fracture, Yielding, Buckling, Reliability, 4340 steel, Damage tolerance, Critical crack, and Failures

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INTRODUCTION

Most precision munitions operate safely and as designed. If structures fail, they buckle, yield, crack, or do not move as designed. Figure 1 shows a yield failure in a normally-flat mortar fin. Root cause investigation showed that unequal pressures on different sides of the fin caused high bending stresses in the fin and yield failure (ref. 1). Figures 2 and 3 show the fracture failures. The failure in figure 2 was caused by a critical defect at a press-fit interface. The crack shown in figure 3 occurred at a nearly square slot. Root cause investigation indicated that the slot was roughly equivalent to the critical defect size.

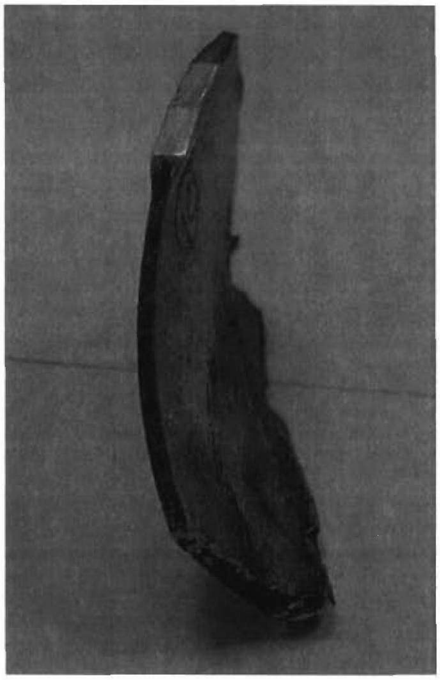

Figure 1
Yield failure in a mortar fin (ref. 1)

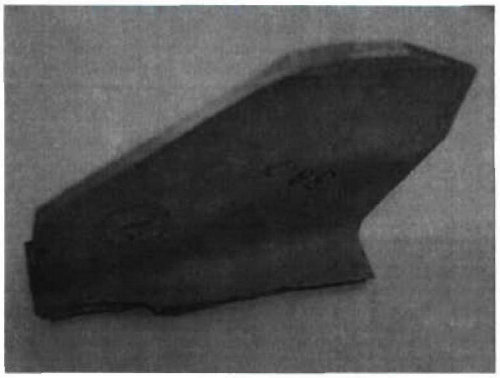

Figure 2
Fracture failure near a mortar fin (ref. 1)

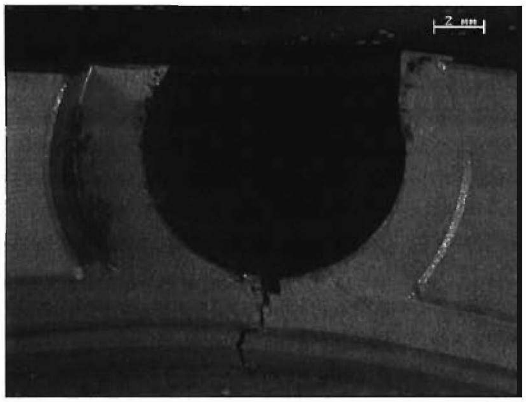

Figure 3
Fracture failure near a slot

Gun-fired munitions have two statistical requirements that affect structural design. First, munitions are designed to meet operational reliability. Excalibur, for instance, is expected to have an operational reliability exceeding 96%. Second, gun-fired munitions are designed so that failures do not damage the gun or put our soldiers at risk of injury. For Excalibur, the number of allowable safety failures is less than 1 in one million.

This paper describes analysis, design, and development methods to meet the operational and safety goals for structural components. The methods incorporate statistical variations rather than safety factors. Detailed failure criteria and step-by-step procedures for damage tolerant design are presented. Redesign guidelines for early failures are presented.

The methods were developed from dozens of root-cause failure investigations and redesigns. Most of the investigations were based on the Army's Sense and Destroy Armor (SADARM), Excalibur, and mortar programs. SADARM was a 155-mm smart sub-munition projectile. Although the SADARM program was cancelled in 2001 because the reliability was 77% versus a requirement of 80%, approximately 300 M898 SADARM projectiles were successfully deployed in 2003 during Operation Iraqi Freedom. Excalibur is the current 155-mm precision guided projectile, in the later stages of design and development in 2006. The mortars programs are mature production programs that have experienced launch anomalies. This paper includes examples from all three programs.

ANALYSIS METHODS FOR GUN-FIRED STRUCTURES

Systems and Sub-systems

Parts and sub-systems are divided into one of two categories: mission-critical parts and safety critical parts. All parts are assumed to be mission critical and are designed to operate after statistically expected applied loads. Mission-critical parts are designed to resist buckling and yielding.

Safety critical parts are structural members whose failure would result in damage to a gun or injury to a soldier. Safety-critical parts must be damage tolerant. For Excalibur, safety-critical parts include the projectile base and walls. Parts within the projectile whose damage results in failure of the projectile walls are also safety critical parts. Low mass parts and contained parts are not considered safety critical. For the most part, this definition of safety critical parts is consistent with the NASA Technical Standard for the Space Shuttle Payload (ref. 2).

Gun-fired munitions are complicated assemblies with multiple parts, complex geometries, and non-linear behavior. Excalibur for instance, has well over 1000 parts, if one includes solder, computer chips, wires, and supporting structures. The geometry is generated in Pro/Engineer (ref. 3). From Pro/Engineer, *.stp files are written as input for finite element analysis. Finite element analysis is usually completed on subassemblies. Wires are not included in the analysis. Bolts are rarely modeled. Threads are not included in the assemblies, but may be evaluated separately in focused finite element models. Holes and notches are retained in high-stress areas. For subsystems with populated circuit boards, the solder is required to correctly model strength, stiffness, and frequencies of the populated circuit boards. O-rings and dampers are included in the analysis of sensors and mechanisms.

The modeling of threaded components usually presents an issue. To simplify the model, it was stated that the threads are not modeled and the surfaces are tied. This can artificially stiffen the structure at times or can change the load path. The best way to handle this situation is to build a two-dimensional model with the threads modeled explicitly. The threads are usually modeled without the helical twist unless it is absolutely necessary. If the helix is required, then the threads must be modeled in a three-dimensional model. These results can then be compared to the simplified model to see the effect of the different geometry.

Software Packages

Design requires accurate prediction of stress, strains, displacements, and critical defect sizes. For most analysis, the Army's Excalibur team uses Pro/Engineer (ref. 3) for solid modeling, NASGRO (ref. 4) for estimating critical defects, and UniPass® (ref. 5) for estimating structural reliability. For finite element analysis, the team uses ABAQUS (75%), ANSYS (20%), or DYNA (5%) (refs. 6 and 7). ABAQUS is preferred because:

- Parts can be de-featured and re-featured
- Explicit or Implicit dynamic, static, or modal analysis can be completed with only small changes to the model
- Parts can be replaced with redesigned parts in an assembly
- Elastic-plastic material and buckling are easy to evaluate
- Contact in ABAQUS Explicit is automatic and easy to implement
- Actual acceleration curves can be used as applied loads
- The new (2005) fracture capabilities can be used to predict critical flaw sizes in highly stressed areas where linear elastic fracture mechanics may not be sufficient

Finite Element Models

Early Analysis

Finite element analysis is used to evaluate the 'actual' assembly. To the extent possible, the analysis is the final geometry. Geometric changes late in the design process are more difficult to accommodate in the finite element model.

Symmetry

Most finite element analyses are completed on three-dimensional models. Symmetry is used when geometry, loads, and materials are symmetric or nearly so. Half-models are required if transverse loads or blow-by are considered. For sensors and mechanisms that are not symmetric, the full model is evaluated. For threaded connections and joints, axi-symmetric models are often used to check details that would otherwise be too costly to include in a three-dimensional analysis.

Meshing

ANSYS and ABAQUS both have automatic meshing ability. In ANSYS, the Structural Error option is checked and corrected until it is below 10%. In ABAQUS, maximum artificial strain energy is usually checked for each part and corrected if it exceeds more than about 10% of the strain energy in the part. When possible:

- Parts are modeled as 8-node brick elements. For regions that cannot be meshed into brick elements, 10-node tetrahedral elements are used.

- Projectile walls, circuit boards, and other parts with bending are modeled with at least four brick elements through the thickness. If mesh refinement is in order, an even number of elements are modeled in the thickness direction.

- If plasticity occurs, the mesh is refined until at least five elements have plastic strain.

- Contour plots are checked to verify that variations within elements are small. The von Mises stress and the stress components are compared with and without averaging.

Material Models

In the absence of statistical material properties, analysis uses the strengths and stiffness from "Metallic Materials Properties Development and Standardization" (ref. 8). Properties are chosen as A-basis minimum, which corresponds to 95% confidence limit on 1% of the distribution (ref. 9). Consideration of component size and manufacturing process are accounted for when picking material strengths and elongations.

For safety-critical parts, the yield strength, ultimate tensile strength, elongation, and fracture toughness are part of the component specification. Parts are tested for compliance using ASTM Standards E-8 or ASTM-E399 (ref. 10). Parts that do not meet strength and toughness requirements are discarded or marked for firing at a lower charge. IThis is only allowed under controlled developmental test conditions.) If the material does not meet strength or toughness requirements during production the material is scrapped. It should be noted that Rockwell hardness does not always correlate well with strength. Rockwell hardness is an indication that the material was heat treated, not that the strength meets specification requirements. Hardness is not used as acceptance criteria.

If statistical analysis is available, statistically-lower values are used instead of handbook values. For 4340 ASM 6414 steel, for instance, reference 8 specifies a yield strength, ultimate tensile strength, and elongation of 1498 MPa, 1795 MPa, and 10%, respectively. For Excalibur, strengths of 1416 MPa, 1623 MPa, and 5.4% were used for initial design. Table 1 shows the results of early material tests. Data was from different vendors and on different structural components. Even with the lower allowable values, parts were fired at reduced charges when 8/66 prototypes had lower-than-required yield strengths.

Table 1
Tested material properties of 4340 steel

	Yield strength	Tensile strength	Elongation	Fracture toughness
	MPa	MPa	%	MPa√m
(No. of samples)	(66)	(66)	(64)	(60)
Average	1501.6	1861.4	11.6	52.2
Standard deviation	78.07	129.88	0.02	11.98
Coefficient of variation	0.052	0.070	0.19	0.230
Minimum required	1416	1623	5.4	45
Handbook (ref. 8)	1498.4	1795.3	10	
No. below minimum	8	2* very close	0	13

The statistics are also used to improve the material properties. For the results in table 1, the lower fracture toughness corresponded to higher phosphorous and sulfur contents. Toughness was improved by removing material lots with sulfur and phosphorous exceeding 0.015%.

Yield strength, ultimate tensile strength, and elongation values are modeled using multi-linear stress-strain behavior. In ANSYS, the 'miso' option is used for elastic/plastic metals and the engineering strength and elongation values are used. In ABAQUS, the engineering values are converted to true stresses and strains. Figure 4 shows the stress/strain diagram for ABAQUS and 4340 steel components. The stress-strain behavior flattens at the ultimate tensile strength. If a bilinear model is used instead, the stress may increase beyond ultimate tensile strength.

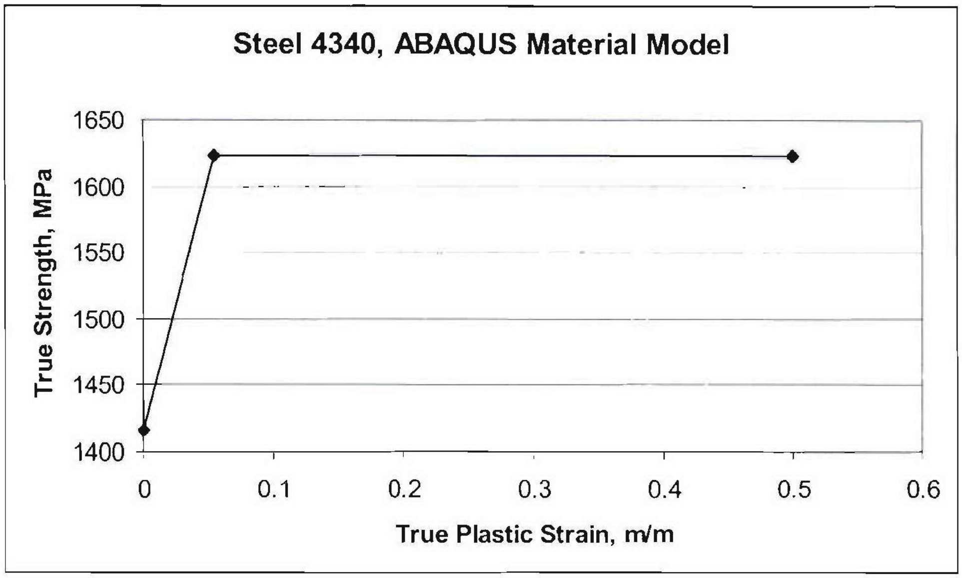

Figure 4
Steel 4340 material model, ABAQUS

Internal Constraints

Internal constraints are a source of uncertainty. Assumptions about internal constraints can result in stress variations as high as 50%. Threaded joints are often modeled as tied surfaces. Other surfaces are modeled as contact surfaces. Bolted connections are tricky - with uncertainty as to what part of the surfaces stay in contact over time. Most of the time, bolted connections are modeled as combined tied and contact surfaces. Analyses are often checked using different constraint assumptions to bracket the solution.

Gun-fired munitions have many parts and many contact surfaces. Since contact can be modeled automatically in ABAQUS Explicit, static analyses are completed as quasi-static. Quasi-static loads are ramped up using the 'smooth' option in ABAQUS Explicit. The time required for loading is about 0.003 sec or 10x the lowest natural frequency of interest. For most contact, friction is neglected.

Applied Loads, Mission Critical Parts and Subsystems

For the Army's Excalibur projectile, all parts are designed to operate after a load 5% higher than can be statistically expected, the Army's 'PMP +5%' load. Permissible maximum pressure (PMP) +5% refers to 105% of the PMP in a weapon as defined in International Test Operating Procedure (ITOP) 4-2-504. Permissible maximum pressure coincides with a 3-sigma upper limit on the service charge conditioned to +145°F. Statistically, PMP load occurs 13 in 10,000 firings and PMP +5% occurs slightly under one in a million firings (refs. 11 and 12).

Applied Loads, Accelerations in the Gun Tube

Figure 5 shows measured accelerations from an on-board recorder on Excalibur, PMP +5% charge. Accelerations were recorded in three perpendicular directions at a location about two-thirds of the distance from the base of the projectile. During set back, the maximum pressure occurs. After set back, the projectile passes the bore evacuator where a pressure pulse occurs (ref. 13). During muzzle exit, the projectile exits the gun tube and the pressure drops to zero. After the pressure drops, the projectile oscillates about its center of mass [fig. 6 (ref. 14)]. The recorded accelerations can be used as applied loads on subsystems near where the data was recorded.

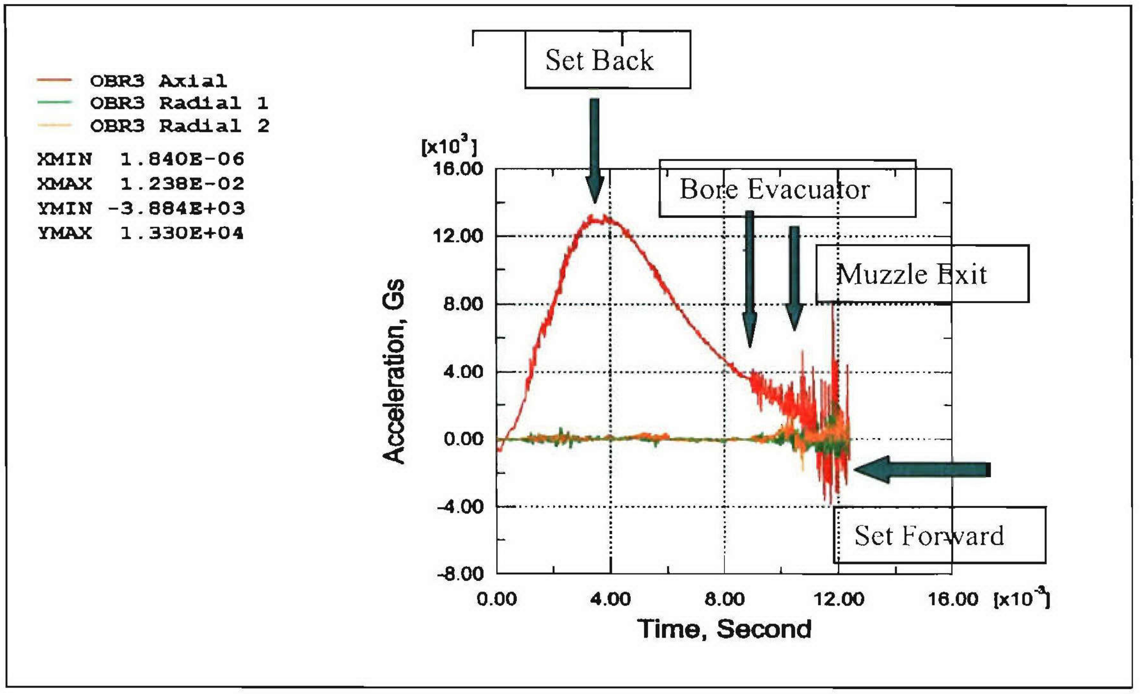

Figure 5
Recorded acceleration, Excalibur, and illustration

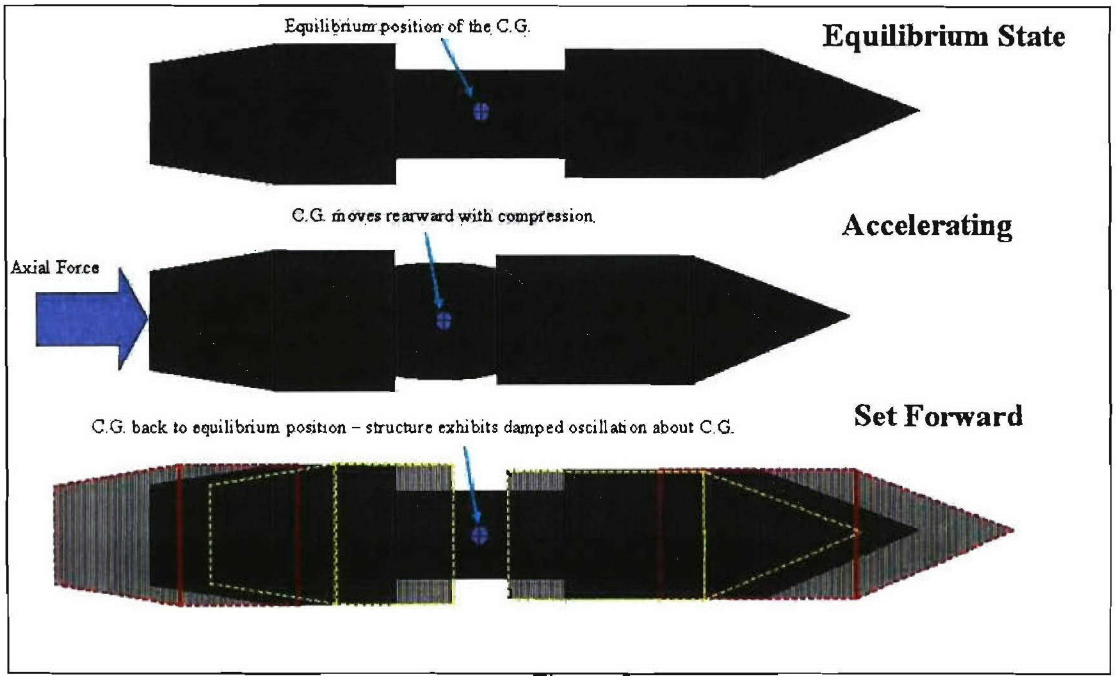

Figure 6
Muzzle exit behavior as pressure drops

For Excalibur, 10 early shots were made at the PMP+5% charge level. For the 10 shots, the coefficient of variation on the maximum axial acceleration was about 0.1. For muzzle exit, the coefficients of variation for the axial and transverse accelerations were 0.47 and 0.43, respectively. Variations in the muzzle-exit dynamics can be attributed to a drop-off of pressure as the projectile passes the bore evacuator and nears the end of the tube. At muzzle exit, the constraint on the structure changes as the projectile goes from support at two bourrelets, to support at one bourrelet, to free flight. The coefficients of variation for set back and muzzle exit were typical of other charge levels for Excalibur (ref. 15).

Recommended Design Loads, Static Analysis

Statistical variations should be considered for safety-critical parts or if reliability is a key design parameter. Statistics can be determined from analytic models and a design of experiments or they can be derived from experimental data. As an example, the following load cases were derived from Excalibur test data:

Case 1. Set back, maximum axial acceleration plus transverse acceleration in the worst direction. For Excalibur for instance, the 99% confidence values were determined from 10 live-shots. For Excalibur, the set back loads include simultaneously (ref. 11):

- Axial Acceleration: 16,566 g's
- Transverse Acceleration: 707 g's

Case 2. Muzzle exit, minimum axial acceleration and maximum transverse acceleration. For Excalibur, the 99% confidence values for muzzle exit are both (ref. 11):

- Axial Acceleration: -5569 g's
- Transverse Acceleration: 6100 g's

Case 3. Blow-by, maximum axial acceleration plus blow-by along the projectile structure. For Excalibur, a subcontractor supplied a blow-by curve as a function of distance along the projectile. For analysis, blow-by was applied to 90/360 deg on the assembled structure. A half-model was used for analysis.

Case 4. Spin-stabilized projectiles may require additional load cases. Angular acceleration should be added to the case 1, set back and angular velocity should be added to case 2, muzzle exit.

Case 5. There are non-symmetric pressures in a gun tube. The mortar damage in figure 1 resulted from non-axi symmetric pressures. Pressure transducers around the 120-mm mortar fins showed pressure variations as high as 14 MPa over the 360 deg. Similar variations in pressures were measured around an instrumented 155-mm projectile, XM1073 (ref. 16).

For components such as fins, additional load cases may be required.

Recommended Design Loads, Dynamic Analysis

Typically, dynamic analysis occurs after prototype development and when test data is available. Dynamic analysis is required for parts with natural frequencies near the loading frequencies. For Excalibur, dynamic analysis was completed for all sensors and circuit boards. Dynamic analysis is also required for all mechanisms and sub-systems with moving parts. Numerous dynamic load patterns were applied to the fuze Safe and Arm device on the Excalibur program. For parts that yielded under the set back load, dynamic analysis was also completed. The repeating loads that occur during muzzle exit can cause reversals in the stresses, an increase in the damage zone, and component failure.

The direction of the transverse loads is unknown. For non-symmetric sensors and mechanisms, transverse loads are applied in eight different directions. The stress variation is used to estimate the reliability of electronic components.

Reality Check and Feed Back

To the degree possible, the analyst needs to understand the design, the function of all of the parts, and the interactions between parts. When the analyst is not the designer, iterative evaluations are expected and feedback is required. Contractors and the design teams should review the results, verify that the displacements are reasonable, validate load paths, compare results to actual firings, and determine if failure is likely.

STRUCTURAL FAILURE CRITERIA

Once the analysis is complete, the results are reviewed to determine if 1) the results are realistic and 2) failure is likely. Three types of structural failure are considered: buckling, yielding, and fracture.

Buckling

Buckling is an elastic instability occurring under compressive forces. Buckling is automatically checked with ANSYS or ABAQUS by using the non-linear geometry option. Since most parts are imported from a solid model, the parts are numerically non-symmetric. Parts that are symmetric would require a small (<0.01% of compressive load) side load to initiate buckling.

Yielding

Projectiles are used one-time and are allowed to yield. Two-yield criteria are used for ductile components:

- Total strain or equivalent plastic strain < elongation
- And plastic strain < ¼ wall thickness

The equivalent plastic strain is based on the von Mises yield criteria. The material parameters yield strength, ultimate tensile strength, and elongation are specified on a drawing and tested in each lot for compliance. Multiple-use parts are designed with stresses below the yield strength. Aluminums are often modeled as orthotropic materials with Hill's criteria for failure (refs. 7 and 17).

Brittle Materials

Brittle materials are modeled as elastic-only. The principal stresses are compared to material strengths using the Mohr-Column criteria (ref. 18). Failure in capacitors and computer chips is based on the maximum bending stress and the probability of failure. The software package Unipass® is used to predict the probability of failure based on separate stress and strength variations (ref. 5).

Fracture

Safety critical parts are designed to prevent fracture failure. The critical flaw size and the associated fracture toughness are specified. The critical flaw size is determined using linear elastic fracture mechanics:

$$K_{IC} \geq \sigma\sqrt{a_c * \pi} * f(a,W,B,D,t)$$

where

K_{IC} = Fracture toughness

σ = Normal stress component, not principal stress

a_c = critical crack size

$f(a, W, B, D, t)$ = function of geometry

The fracture toughness K_{IC} is chosen as a statistical low value and verified by tests. Details of the damage tolerant design method follow.

DAMAGE TOLERANT DESIGN FOR SAFETY CRITICAL PARTS

Overview, Damage Tolerant Design

In damage tolerant design, the engineer assumes 1) that a flaw smaller than a critical size may be present and 2) the munition should operate safely and reliably with the flaw present. The rate of flaws is relatively low. In a recent mortar projectile sorting, for instance, 100% of 24,300 mortar bodies were x-rayed for defects. Fifty-nine parts had defects. All defects were smaller than the critical size. Figure 7 shows a sample with a defect.

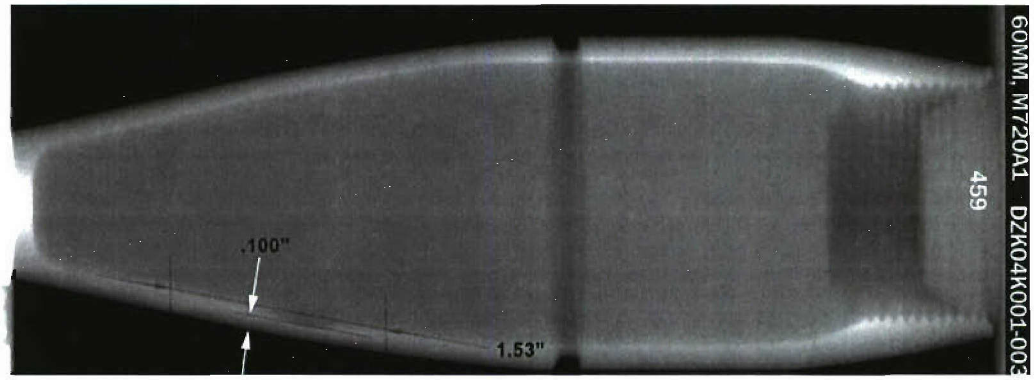

Figure 7
Defect in a mortar body, smaller than critical size

Figures 2 and 3 also show typical sites for fracture failure. Figure 2 is a press fit. If debris is trapped between the metal surfaces, sliding the parts together can cause a critical defect. In figure 3, the critical defect corresponded to a design detail. Damage tolerant design could have prevented the early development failure that occurred at eight out of eight rectangular slots during a PMP+25% Excalibur firings.

Method, Damage Tolerant Design

Critical crack sizes are estimated using the linear elastic fracture mechanics assumptions. The amount of plastic deformation is assumed to be small. The following procedure is used to estimate the critical crack size:

Step 1, Complete Stress Analyses

Finite element analysis is used to find the stress distribution in the safety critical parts. Several load cases are evaluated to determine the critical case for different locations. The analysis includes material and geometric nonlinearities.

Step 2, Record Tensile Stresses

Normal stresses (not principal stresses) are recorded at high stress locations. For cylindrical components, the hoop and axial stresses are required. This may require a stress transformation when processing the results.

Step 3, Determine Dimensions at Critical Locations

For cylindrical parts, inner and outer radius is required. For holes, threads, and notches, other dimensions are required.

Step 4, Estimate Statistically Low Fracture Toughness, K_{IC}

A number of references give for fracture toughness values (refs. 4, 8, 19, and 20). For 4340 steel, reference 4, Version 3.0, gives a chart value of 60 MPa√m, reference 19 gives values between 60 and 77 MPa√m , and reference 20 gives K_{IC} of 44.5 MPa-√m. "Metallic Materials Properties Development and Standardization [MMPDS (ref. 8)] gives toughness values for many aluminum and titanium alloys, but not for 4340 steel. Fracture toughness variations are generally higher than other material parameters. If available, statistically low K_{IC} values are chosen to minimize waste. The preferred toughness reference is the NASGRO program, which includes statistics on toughness for common aerospace materials (ref. 4). The procedure is as follows:

- Module: Material data processing, NASMAT program, toughness data, valid K_{IC} data is chosen

- For the correct material, entries in the range of yield and ultimate tensile strength are chosen. For 4340 steel, 20 entries were used to find the statistically low value. Toughness is specified as the average value minus 2 standard deviations. For 4340 ASM 6414 steel, the toughness was chosen to be 42 MPa√m. Figure 8 shows the results of early toughness tests on Excalibur components. Thirteen of 60 samples were discarded or used with a lower charge. Once the early test data was available, process improvements were implemented to reduce material variation.

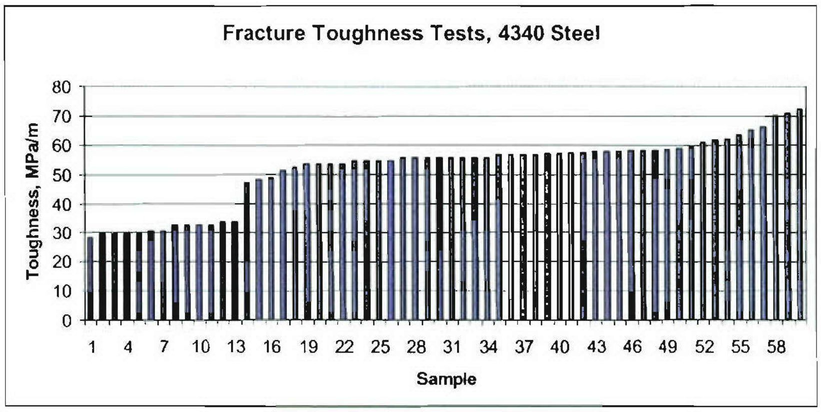

Figure 8
Fracture toughness test results, 4340 steel

Step 5, Estimate Critical Crack Dimensions

Critical crack sizes are initially predicted assuming standard geometries and linear elastic fracture mechanics. Linear elastic fracture mechanics is valid when the hoop and axial stresses are below about 80% of the yield strength.

Since the geometry of actual parts rarely matches a theoretical case, a number of 'close' geometries are evaluated and the smallest crack size is chosen as critical. Figure 9 shows a typical high-stress location in a cylindrical component. The part has two notches. The highest stresses are in the notch and the stress varies through the wall thickness.

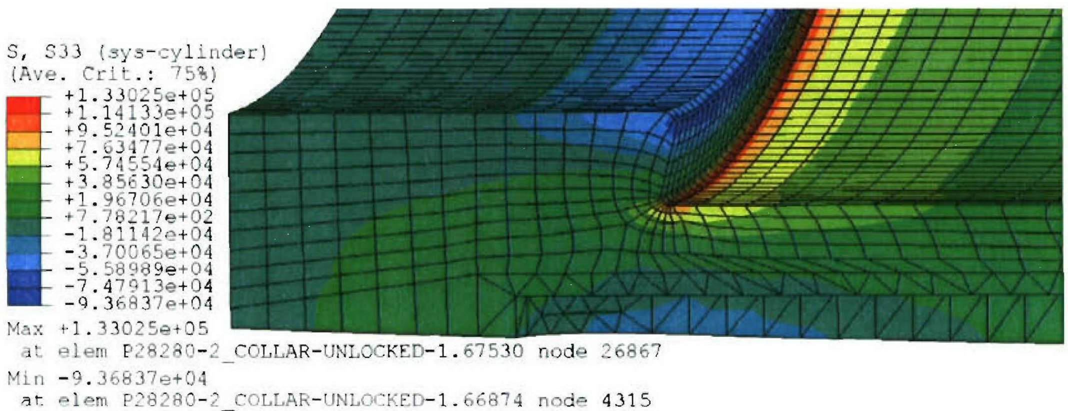

Figure 9
Tensile stress distribution at a critical location

There is no closed-form solution for the geometry shown in figure 9. Typical 'close' crack configurations are found in the NASGRO software package and in a number of fracture references (refs. 4, 20, 21, 22, and 23). Close configurations are used to estimate the maximum flaw size that can be supported during the expected load. The following cases are considered:

- In NASGRO module NASCCS, 'Critical Crack Size', Surface Cracks SC01 and SC02 (fig. 10). Surface cracks are given in terms of a crack depth to width ratio (a/c). Crack depths are found for a/c ratios of 1.0 and 0.1. Both SC01 and SC02 include variations in the normal tension stress as a function of thickness. For cylindrical parts, the stresses S_0 and S_1 in figure 10 are determined from the stress at the inside and outside wall of the cylinder. The analysis can be repeated for both hoop and axial stress components, if they act in tension. NASGRO case SC02 includes the nonlinear stress variation through the wall thickness. This can be taken from the *odb file in ABAQUS.

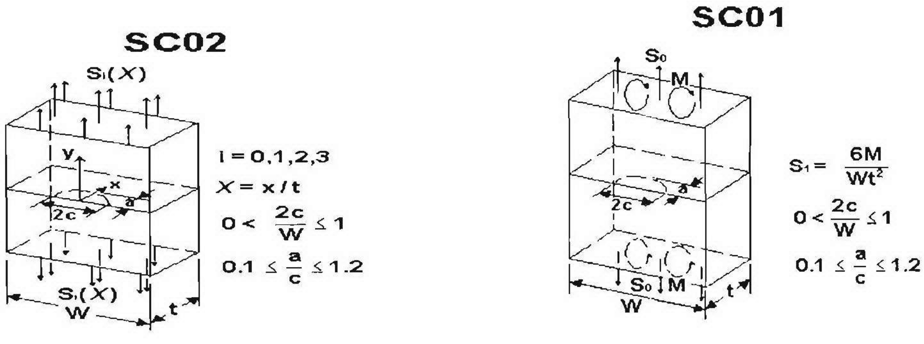

Figure 10
NASGRO (ref. 4) surface cracks (copied with permission)

- NASGRO Corner Crack CC01 is used for notches and edges (fig. 11).

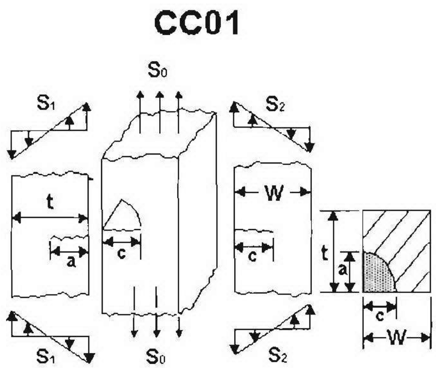

Figure 11
NASGRO corner crack CC01 (ref. 4), varying stresses

- For cylindrical geometries, NASGRO cases SC04, SC05, and SC06 are also evaluated as shown in figure 12. Surface cracks on the inside and outside of the part are considered. Crack SCO3 applies specifically to spherical pressure vessel. As an approximation, the group uses SCO3 for cylindrical parts with pressure on the crack surface.

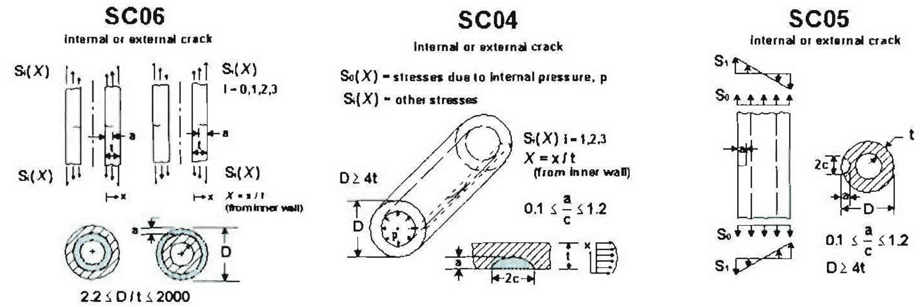

Figure 12
NASGRO (ref. 4) surface cracks for cylinders

- For threaded cylindrical regions, NASGRO cases SC08, SC09, and SC10 are evaluated (fig. 13).

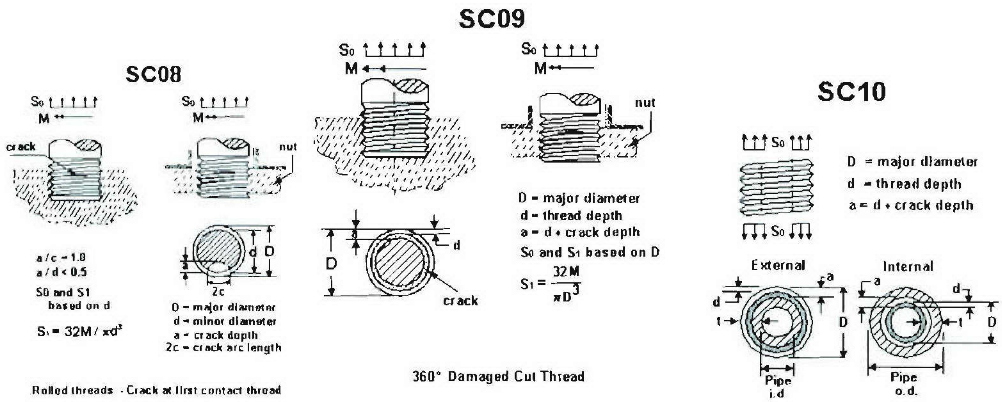

Figure 13
NASGRO (ref. 4) threaded cylinders

- At bolt holes, NASGRO cases SC11, CC02, CC04, CC01, TC03, TC05, and TC09 are evaluated. Some of these cases are shown in figure 14.

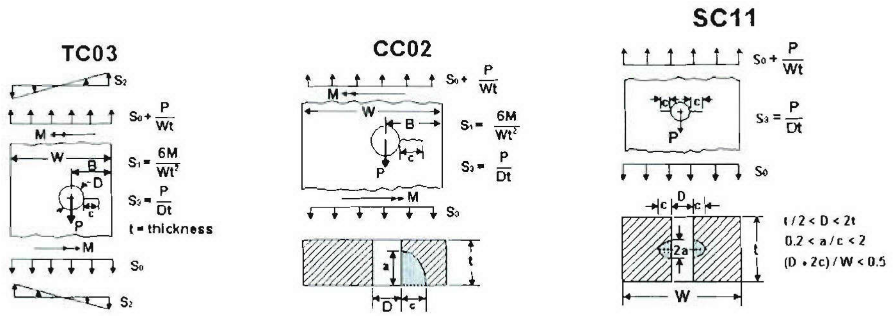

Figure 14
Some of the NASGRO (ref. 4) cases evaluated at a hole

- Other cases are evaluated using a FORTRAN package written at the U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, New Jersey. The FORTRAN program considers surface cracks and cracks in cylinders from Anderson's *Fracture Mechanics* (ref. 21) book. Generally, Anderson's figures 12.2, 12.29, 12.30, and 12.31 are evaluated from the reference. The two crack cases in Shighley are also checked (ref. 18). References 23 and 24 are used for holes with cracks on one or two sides and miscellaneous plate problems.

- Many of the critical crack locations have stresses approaching the yield stress. The FORTRAN program includes a plate with a surface crack and the Irwin plastic zone correction (refs. 25 and 26). The program also includes a part-through crack in a cylinder with the Irwin plastic zone correction (ref. 22).

Step 6, Recommend Critical Flaw Sizes

Critical defect sizes can be recommended at different high stress locations and for the remaining part. Generally, the smallest flaw size is the critical size. The resulting crack map generally specifies a crack depth that is half of the size recommended by the design team.

For most critical defect locations, the different geometry assumptions provide similar critical crack size estimates. For the example shown in figure 8, the following cases gave similar critical crack sizes: the part-through crack in a plate with the Irwin correction, the part-through crack in a cylinder with an Irwin correction, NASGRO SC01, NASGRO SC06, NASGRO CC01, and NASGRO EC01.

Redesign may be recommended if the flaw size is too small for the inspection methods used by the contractor. For instance, one of Excalibur's contractors uses reference 27] and inspects for defects larger than:

- a/c = 1.0, a = 1.9 mm

- a/c = 0.1, a = 0.56 mm

A recent NASA publication on dye-penetrant tests suggests smaller allowable flaw sizes for dye-penetrant (ref. 28). The following NASA rejection criteria are suggested for locations where a critical defect is not otherwise specified:

"a. <u>Linear indications</u> - all linear indications, regardless of length, shall be cause for rejection of the component.

b. <u>Single rounded indications</u> - a single rounded indication greater than 0.030 inches in diameter shall be cause for rejection of the component.

c. <u>Multiple rounded indications</u> - two or more rounded indications each less than 0.030 inches in diameter but separated by less than 0.030 inches shall be cause for rejection of the component."

Similar recommendations could be applied to the safety-critical parts of gun-fired components.

Linear elastic fracture mechanics is an estimate not an exact prediction. If the geometry and loading matches the theoretical crack assumptions and the normal stresses do not exceed 80% of yield, then the critical crack predictions are probably reasonable. For some parts, elastic/plastic fracture mechanics is also done. Elastic/plastic fracture mechanics is more accurate, since it is completed on the finite element geometry. It is more time consuming since each crack configuration must be modeled separately. Elastic/plastic analysis may be done if:

- The normal stress exceeds 80% of yield
- The match-up in theoretical and actual geometries is poor
- The critical crack size is too small for the vendors non-destructive evaluation method and a double check of the crack size is requested
- The required inspections would be costly and a large critical crack size might save the government money

Two methods of elastic/plastic fracture are available in ABAQUS and both are used. The crack can be modeled with singularities at the crack tip. This method is easier to implement on a flat part. ABAQUS 6.0 and higher has automatic meshing to map in the elastic and elastic/plastic singularities. The chosen crack length is either the critical crack length or the length visible by the supplier's non-destructive testing technique. The method must be repeated for each different crack configuration. The second type of analysis is also supported by ABAQUS version 6.0 and higher and is the cohesive stress method introduced by Dugdale (ref. 29) and Barrenblatt (ref. 30). This method can be implemented on cylindrical geometries. It requires a relatively fine mesh and different crack configurations require different models.

OPERATIONAL FAILURE CRITERIA DUE TO TOLERANCE VARIATION

One additional structural failure is checked using statistical methods. Precise munitions have sensors and mechanisms that must deploy or activate when triggered, generally during the flight. Examples include the fuze safe and arm (FSA) device and sensors. The 155-mm M898 SADARM projectile experienced some failures when its thermal sensors failed to deploy during some shots. Investigation showed that when several tolerances were machined near to their limit, binding occurred and the lens failed to activate. To improve the reliability of Excalibur, statistical analysis is used to check the probability of a tolerance stack-up failure (refs. 5 and 31).

DEVELOPMENT AND EARLY TESTING FOR RELIABLE STRUCTURES

Defining Test Failures for Reliable Designs

Testing is an integral part of designing for reliability. In the early stages of development, the severe testing environment results in early failures, redesign, and retesting. With hundreds of parts, variable dynamics, and multiple vendors, failures are difficult to prevent. Operational failures are easy to detect - the munition does not meet a key performance parameter. Reliable munitions require a broader definition of failure:

- Any failure to operate as designed
- A small failure that might vary into an operational failure

Consider the Space Shuttle Columbia. For years, small pieces of foam were breaking free without causing operational failure. In February 2003, a large chunk broke free causing catastrophic damage (ref. 32). The Columbia Accident Review Board reported that "Foam loss has occurred on more than 80% of the 79 missions for which imagery is available ..." The Space Shuttle Challenger had a similar tragedy. The coldest launch of a space shuttle was Space Shuttle Challenger, mission 51-L, which occurred at 36°F (ref. 33). The Challenger accident report stated:

> "Of 21 launches with ambient temperatures of 61 degrees Fahrenheit or greater, only four showed signs of O-ring thermal distress; i.e., erosion or blow-by and soot. Each of the launches below 61 degrees Fahrenheit resulted in one or more O-rings showing signs of thermal distress."

Failure of the O-rings was found to be the root cause of the Challenger failure. Both space shuttle disasters were preceded by non-operational failures similar to the catastrophic failure.

It is important for the designer to examine successes as well as failures to assure a robust design. The fact that a given test was successful does not mean that all components functioned as designed or that an anomaly did not occur. The prudent designer should examine all hardware recovered from firings and verify that it behaved as the structural model predicted. If it did not, there may be something wrong with the model and experience has taught us that innocuous items that misbehaved usually end up as full blown failures later.

Similar warning signs have been noted in the Excalibur program. Capacitors and chips noted after operational successes have been followed by similar failures. Similar small difficulties with the base have been followed by more substantial difficulties.

Figure 15 describes a lesson learned from the SADARM program. Again, small failures occurred and operation was otherwise acceptable. Eventually, however, the small failures escalated into operational failures and sub-munitions were lost. The Key Performance Parameter, reliability, for SADARM was not met.

SADARM Lessons Learned
J. Kalinowski, December 2002

1. Subject Title: Failure to implement Corrective Actions (CAs)

2. Problem Description: During SADARM development the system contractor failed to implement CAs to hardware that was not functioning as designed since it had not caused a system failure.

3. Problem Cause: The Despin, Decelerate, Orient & Spin (DDO&S) system of the SADARM submunition (SM) was not functioning as designed. During early testing, video coverage of the descending SADARM munition (SM) showed the Ram Air Inflated Device (RAID) descending in the vicinity of the SM descending under the Vortex Ring Parachute (VRP). Although no apparent interaction was observed during testing, several "close-calls" were noted. The system contractor felt that no fix was necessary since no SM failure resulted from these "close-calls". During subsequent testing these "close-calls" became direct impacts between the RAID and the SM under the VRP which resulted in wrapped VRPs and system failures for the SMs. Although system failures were eminent, it wasn't until the occurrence of "hard-failures" that the system contractor took action.
In addition, this condition caused the SM to impact the ground at a much greater velocity than it would have if the VRP hadn't wrapped. This condition made it difficult to distinguish between electronics failures due to gun launch and ground impact.

4. Solution: *None. Problems were not addressed until "hard failures" occurred.*

5. Future problem avoidance: Conduct Fault Tree Analysis on all items not functioning as designed as soon as the deficiency is noted and implement corrective action into the design as soon as possible. Fixing deficiencies early allows for more data to be collected on the fix and the other subsystems to be evaluated.

Figure 15
Lessons learned, failure to implement corrections

Investigate Root Cause of Failures

There is no point in fixing the wrong problem or in fixing a problem incorrectly. Root cause investigations provide a procedure to determine the source of a failure and implement changes to keep the failure from recurring. The steps include:

1. Brain storming as a multi-discipline team
2. Fault tree analysis
3. Definition of plausible failure sequences
4. Data gathering
5. Assessing refuting and supporting data for plausible failure sequences

6. Determination of the likely root cause(s) of the failure

7. Implementing corrective action

The process often uncovers several required design improvements.

Redesign to Prevent Future Failures

Late in the design process, most upgrades are process-specific or material changes. Geometric changes are more difficult to implement. For the material changes, the root cause (fracture, yield, or buckling) must be known. If fracture is the root cause, choosing a higher-strength material may result in reduced toughness. Choosing a higher-strength steel, if the original design was steel, would also not improve a buckling problem. Summarizing, typical redesign recommendations include:

- Choosing a stronger material if the root cause of failure was yielding
- Choosing a higher-modulus material if the root cause of failure was buckling
- Choosing a tougher material if the root cause of failure was fracture
- Clarify, modify, and improve the manufacturing process to reduce variations
- Improve quality control methods
- If possible, avoid potting materials and adhesives. If not possible, clarify the process to reduce variations
- Design connections so they can not shake loose
- Avoid adhering materials with different Young's moduli or different coefficients of expansion
- Avoid rectangular holes and sharp corners
- Avoid press fits or consider damage tolerant design and improved manufacturing processes
- Avoid designs that keep highly stressed regions in tension for long periods of time

Test a Statistically Meaningful Quantity

Testing is expensive. Firing 10 Excalibur prototypes at Yuma Proving Ground is expensive. The high cost of testing is the reason for finite element analysis and attention to the modes of failure in the redesign effort. As described in another Lesson Learned from the SADARM program (fig. 16), tests should be done after implementing several design changes. With reliability goals of 90% and greater, it is recommended that at least 10 munitions be tested to validate blocks of improvements.

SADARM Lessons Learned
J. Kalinowski, December 2002

1. Subject Title: Inadequate test quantities masked whether or not the fixes were effective.

2. Problem Description: During SADARM development, the effect of fixes to the hardware was masked by successes demonstrated on small sample sizes.

3. Problem Cause: During SADARM development, a rigorous test-fix-test program was initiated. During this program many tests were conducted at high charge zones to precipitate reliability deficiencies. Many of these tests were conducted with few samples (usually less than five projectiles). Initially, many of the fixes appeared to be effective at solving the deficiency. This success however was short lived since the same problems would emerge during subsequent test iterations (i.e. FS&A, IR Telescope deployment, etc.). In addition, many of the problems that we were trying to fix were failures that were contributing to less than 10% of the reliability deficiency (i.e. low-occurrence failures).

4. Solution: Maximize test quantities by implementing block-changes to the hardware. This allows several iterations to be combined which allows for a more statistically significant sample size to be tested. Sample sizes should demonstrate the statistical success of fixes to the hardware.

5. Future problem avoidance: Testing larger quantities by implementing block changes aids in reducing test costs, allows for a better evaluation of the fix by providing larger sample sizes, and reduces the probability of a marginal fix being accepted and having to be fixed again.

Figure 17
Lesson learned, number of tests required

CONCLUSIONS

For more reliable smart munitions, the following recommendations are made:

1. Do finite element analysis as early in the design processes as possible
2. Verify that the finite element results are realistic
3. Design all structures to resist three modes of structural failure: yield, buckling, and fracture
4. Use damage tolerant design for all safety-critical components
5. For parts that move, use statistics to check tolerances and verify motion
6. During testing, think of small failures or anomalous behavior as possible variations of larger failures
7. Use root cause analysis to determine the nature of the failure and redesign for the failure modes that occurred
8. Test statistically meaningful quantities to verify fixes

REFERENCES

1. Cordes, J.A.; Rand, H; Carlucci, D.; Reinhardt, L; and Kerwien, S., "Predicting the Cause of Failure in 120-mm Mortar Fins," Technical Report ARFSD-TR-03002, U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, Precision Munitions and Demolition, July 2003.

2. "Fracture Control Requirements for Payloads Using the Space Shuttle", NASA Technical Standard, NASA-STD-5003, 1996.

3. Pro/Engineer Wildfire 2.0, PTC, 140 Kendrick Street, Needham, MA, 02494, 2005.

4. NASGRO Version 4.13, SWRI Main Office, 6220 Culebra Road, P.O. Drawer 28510, San Antonio, Texas 78228-0510, Phone (210) 684-5111, licensed 2005.

5. Unipass Version 5.52, PredictionProbe, Inc., 2192 Dupont Dr., Suite 205 Irvine, California 92612, licensed 2005.

6. ANSYS®, Release 8.1, 2004.

7. ABAQUS, Version 6.5.6, ABAQUS, Inc, Providence, RI, 2006.

8. "Metallic Materials Properties Development and Standardization (MMPDS)," Department of Transportation Report DOT/FAA/AR-MMPDS-01, January 2003.

9. Rice, R.C.; Goode, R.J.; Bakackas, J.G. Jr.; and Thompson, S.R., "Development on MMPDS Handbook Aircraft Design Allowables," Conference on Aging Aircraft, New Orleans, LA, September 8-11, 2003.

10. 1995 Annual Book of ASTM Standards, Volume 3.01, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA, 1995.

11. Cordes, J.A.; Vega, J; Carlucci, D.; and Chaplin, R.C., "Design Accelerations for the Army's Excalibur Projectile," Technical Report ARAET-TR-05008, U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, June 2005.

12. International Test Operations Procedure 4-2-504(1), Ad No. A274371, 19 October 1993.

13. Carlucci, D.; Vega, J.; and Cordes, J.A., "Effect of a Bore Evacuator on Projectile In-Bore Dynamics," Technical Report ARAET-TR-04017, U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, November 01, 2004.

14. Carlucci, D.; Cordes, J.A.; Morris, S.; and Gast, R., "Muzzle Exit (Set Forward) Effects on Projectile Dynamics," ARAET-TR-06003, U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, 2006, unpublished.

15. Cordes, J.A.; Vega, J.; Carlucci, D.; Chaplin, R.; and Peterson, W.S., "Structural Loading Statistics on Live Gun Firings for the Army's Excalibur Projectile," ARAET-TR-05005, U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, Precision Munitions and Demolition, April 2005.

16. Hollis, M.; Flyash, B.; Bahia, A.; Potucek, J.; and Carlucci, D., "Empirical Measurements on Cannon Launch Pressures on a Finned 155-mm Artillery Projectile," 21st International Symposium on Ballistics, 19-23 April 2004.

17. Hill, R., The Mathematical Theory on Plasticity, Oxford University Press, London, 1950.

18. Shigley, J.E. and Mischke, C.R., Mechanical Engineering Design, 5th Edition, McGraw-Hill, Chapter 6, 1980.

19. Damage Tolerant Design Handbook, CINDAS/USAF CRDA Handbooks Operation, Purdue University, In, 1994.

20. Metals Handbook, Volume 1, ASM International, OH, Pg. 434, 1990.

21. Anderson, T.L., Fracture Mechanics, Fundamentals and Applications, CRC Press, Inc, Boca Raton, Fl, 2nd Edition, Pp. 627-636, 1995.

22. Barsom, J.M. and Rolfe, S.T., Fracture & Fatigue Control In Structures, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ, 1987.

23. Tada, H., Paris, P.C., and Irwin, G. R., The Stress Analysis on Cracks Handbook, Del Research Corporation, Hellertown, PA, 1973.

24. Fracture Mechanics Design Handbook, Technical Report RI-77-9, U.S. Army Missile Command, Redstone Arsenal, AL, 1976.

25. Irwin, G.R., "Crack Extension Force For A Part-Through Crack In A Plate," Transactions of ASME, Journal on Applied Mechanics, Series E, Vol. 29, No. 4, Pp. 651-654, 1962.

26. "Fracture Control on Metallic Pressure Vessels", NASA Space Vehicle Design Criteria (Structures), NASA Sp-8040, 1970.

27. Rollis, J.R; Grove, R.K.; Millar, J.A.; Petrakis, D.N.; Price, J.D.; and Wake-Hood, S.J., "Structural and NDE Considerations in the Design of Titanium Satellite Propellant Tanks," AIAA-94-3107, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, June, 1994.

28. Stanley, D.M. and Files, B.S., "Process Specification for Liquid Penetrant Inspection," Engineering Directorate Structural Engineering Division, NASA, PRC-6506 Rev. B. January, 2005.

29. Dugdale, D.S., "Yielding of Steel Sheets Containing Slits," Journal on Mechanics, Physics, and Solids, Vol. 8, pp. 100-104, 1960.

30. Barenblatt, G.I., "The Mathematical Theory on Equilibrium Cracks in Brittle Fracture," Advances In Applied Mechanics, Edited by H.L. Dryden and T. Von Karman, Academic NY, Vol. 7, 1962.

31. Recchia, S.; Cordes, J.A.; Khalesi, M.; and Thomas, J.; "Improving Reliability by Reducing Tolerance Stack-Up Failures," ARAET-TR-05018, U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, January, 2006.

32. Http://Spaceflight.NASA.Gov/Shuttle/Archives/Sts-107/Investigation/Caib Medres Full.Pdf, October 2003.

31. "Report on The Presidential Commission on The Space Shuttle Challenger Accident," Http: //Science.Ksc.NASA.Gov/ Shuttle/Missions/51-L/Docs/Rogers-Commision/Chapter-4.Txt, in compliance with Executive Order 12546 on February 3, 1986.

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